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## Trunnion Rod Microcrack Detection

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**BACKGROUND:** Post-tensioned rods are used to anchor spillway gates and transfer the forces from the reservoir pool through the gates to the spillway structures. Large tensile loads are applied to these high-strength steel rods to compress the surrounding concrete and prevent it from experiencing excessive tensile forces, which are naturally problematic for concrete. These post-tensioned trunnion anchor rods are used extensively for support of tainter gates and considered the standard for the US Army Corps of Engineers (USACE) and other government and nongovernment agencies within the United States and elsewhere. These rods are now experiencing ongoing failures. The Corps of Engineers needs reliable non-destructive testing (NDT) methods that are rapid, robust, and capable of detecting and quantifying defects, as well as methods for determining rod tensions. These methods are required to be rapid because of the large number of rods that exist at some installations. Robustness is required to handle the significant variations in design, construction, and field conditions that are known to exist. Defect detection and quantification provides tracking and monitoring data important for planning and prioritizing remediation efforts or operational practices.

**Purpose of Work Unit.** Research Statements of Need (SONs), 2008-N-9, were submitted by the Corps Research Area Review Group (RARG) to the Navigation Systems Research Program. In response to this SONs, a work unit (WU) was established to develop procedures and specifications to assess post-tensioned anchorage capacity deterioration by means of microcrack detection using nondestructive testing/nondestructive evaluation (NDT/NDE) types of field techniques. The purpose of this research is to develop a field inspection capability for the purpose of detecting and quantifying slowly propagating microcracks in trunnion anchor rods.

Post-tension rod loss occurs as an orthogonal brittle failure when a propagating cross-axial microcrack reaches a critical threshold. For ungrouted rods, this has resulted in rods being ejected under extreme velocities. Heavy retrofit cover box housings have been constructed to help contain failing rods. It is not known if the defect growth and resulting rod failure rate will stay at its relatively low number of a handful per year across the Corps inventory or whether it will increase as older rods continue to be in-service and defects continue to slowly propagate until reaching a threshold total failure point.

A successful NDT method will allow for rapid ultrasonic assessment and tracking of rod defects prior to their catastrophic failure. This effort leverages another ongoing project focusing on seven-strand steel cable failures whose origins are also from aging, early-design, post-tensioned steel systems.

The product of the trunnion anchor rod work unit will be a test method, hardware, and system specifications for successful realization of a system to provide detection of microcracks under

| Report Documentation Page  |                                    |                                     |   | Form Approved<br>OMB No. 0704-0188                  |                                 |
|--|------------------------------------|-------------------------------------|---|---|---------------------------------|
| Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. |                                    |                                     |   |   |                                 |
| 1. REPORT DATE<br><b>AUG 2013</b>  |                                    | 2. REPORT TYPE                      |   | 3. DATES COVERED<br><b>00-00-2013 to 00-00-2013</b> |                                 |
| 4. TITLE AND SUBTITLE<br><b>Trunnion Rod Microcrack Detection</b>  |                                    |                                     |   | 5a. CONTRACT NUMBER                                 |                                 |
|  |                                    |                                     |   | 5b. GRANT NUMBER                                    |                                 |
|  |                                    |                                     |   | 5c. PROGRAM ELEMENT NUMBER                          |                                 |
| 6. AUTHOR(S)   |                                    |                                     |   | 5d. PROJECT NUMBER                                  |                                 |
|  |                                    |                                     |   | 5e. TASK NUMBER                                     |                                 |
|  |                                    |                                     |   | 5f. WORK UNIT NUMBER                                |                                 |
| 7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)<br><b>US Army Engineer Research and Development Center,Vicksburg,MS,39180</b>   |                                    |                                     |   | 8. PERFORMING ORGANIZATION REPORT NUMBER            |                                 |
| 9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)  |                                    |                                     |   | 10. SPONSOR/MONITOR'S ACRONYM(S)                    |                                 |
|  |                                    |                                     |   | 11. SPONSOR/MONITOR'S REPORT NUMBER(S)              |                                 |
| 12. DISTRIBUTION/AVAILABILITY STATEMENT<br><b>Approved for public release; distribution unlimited</b>  |                                    |                                     |   |   |                                 |
| 13. SUPPLEMENTARY NOTES  |                                    |                                     |   |   |                                 |
| 14. ABSTRACT   |                                    |                                     |   |   |                                 |
| 15. SUBJECT TERMS  |                                    |                                     |   |   |                                 |
| 16. SECURITY CLASSIFICATION OF:  |                                    |                                     | 17. LIMITATION OF ABSTRACT<br><b>Same as Report (SAR)</b> | 18. NUMBER OF PAGES<br><b>11</b>                    | 19a. NAME OF RESPONSIBLE PERSON |
| a. REPORT<br><b>unclassified</b>   | b. ABSTRACT<br><b>unclassified</b> | c. THIS PAGE<br><b>unclassified</b> |   |   |                                 |

the conventional field boundary conditions. These observed variations are important and, ultimately, will determine the specific mechanical response and testing accessibility/conditions. The logistics relevant system is described in the next section.

Research indicates that cracks may go through opening and closing stages. These defects need to be detected and damage quantified regardless of whether the crack is in the open or closed condition. When a large crack is closed, the surface-to-surface ‘chatter’ is higher and, hence, the nonlinear influence is greater. If a large diameter crack is pulled into the open condition, the nonlinear parameter becomes lower but the linear detectability will increase. Because of this reciprocal influence with linear and nonlinear system detection capabilities, both are deemed necessary for robust microcrack detection. A hybridization is being pursued to facilitate robust detection and quantification of linear and nonlinear signal influences at significant downrange distances of opened and closed microcracks. Nonlinear based detection must address and incorporate the influence of waveguide-based dispersion effects, which define practical or desirable propagation modes. Tuned longitudinal and/or torsional propagation modes are currently being investigated in a full-scale test bed recently constructed at US Army Engineer Research Center (ERDC). ERDC is also receiving technical support from leading researchers in the fields of nonlinear acoustics and guided wave methods. The collaborators in these areas are Dr. Alexander Sutin of the Stevens Institute of Technology and Dr. Joseph Rose of Feature Based Systems Incorporated.

A more detailed discussion of guided waves is included in the technical section later in this document, as well as information on the integration of guided wave and nonlinear testing, which is seen as one of the technical challenges of this effort. The next section covers rod installation, design and construction variations, and typical embodiment.

**Field Conditions:** EM 1110-2-2702 (USACE 2000) is the current design standard and describes the use of post-tensioned trunnion anchorage. The majority of the Corps projects used a trunnion anchor rod design which requires the rods to be anchored to a metal plate embedded deep within the concrete spillway pier. Often, the rods are threaded into the anchor plate closest to the gate, with a protruding end that is commonly grouted into the mass concrete. The free ends extend through the downstream face of the pier, as seen in Figure 1, and attach the trunnion girder to the pier. The number of rods required for a project is based on the size of the tainter gate and loading conditions. Across various designs and constructions, the tensile and free rod lengths also vary. Tensile rod length sections are known to be as long as seventy feet. The exposed ends also vary greatly from several inches to several feet with rough (field cut) ends also being a common. There is some, but not much, variation in rod diameter, with the majority of rod inventory being 1.25 inches in diameter. The tensioned section of the rod is typically encased in a 2-inch schedule-40 steel pipe, which is filled via injection ports with either thick anti-corrosive grease (such as the current NO-OX-ID A special) or a cement based grout. While newer installations use a threaded nut to load the rod, an older method, and more commonly seen, is a grip-nut assembly which uses a two-part compression wedge with serrated teeth to bite into the steel surface of a smooth rod. These configurations are susceptible to slippage and, as a result, are not available or used.

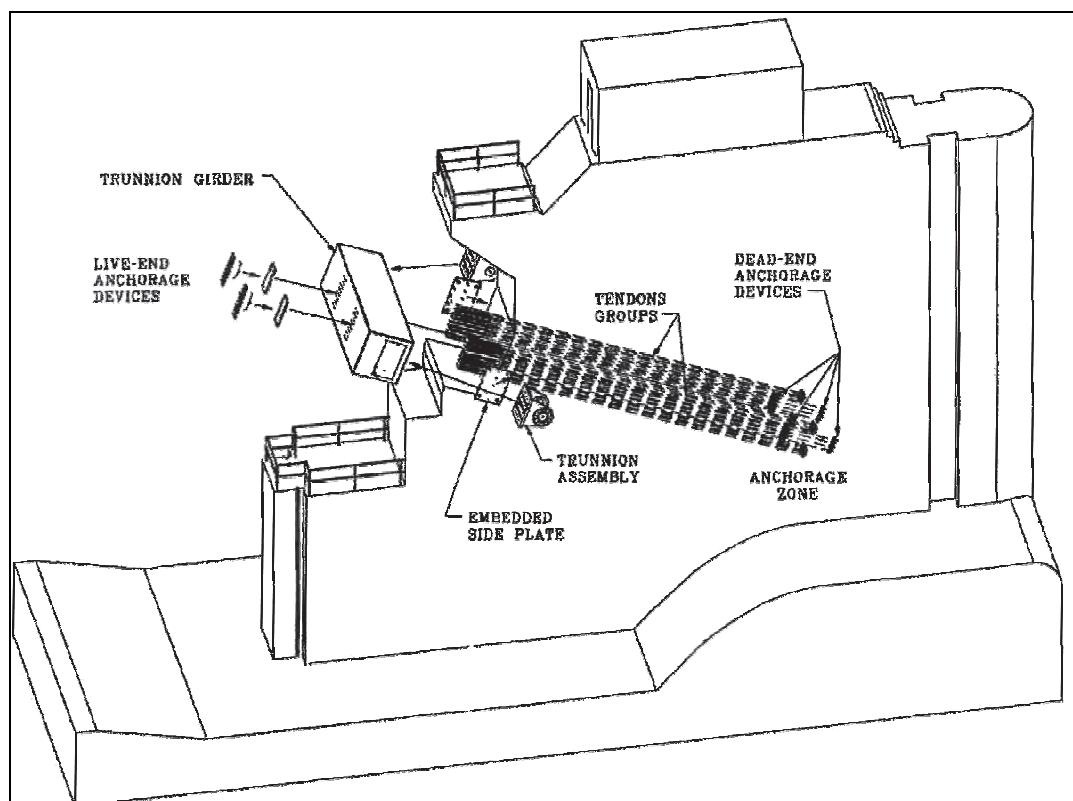


Figure 1. Schematic of trunnion rod anchorage from Figure 5-1 of USACE (2000).

**Existing Technologies for Defect Detection:** After high-strength rods are manufactured, quality assurance testing is typically performed using one or more of various non-destructive testing methods. Typically, these are ultrasonic in nature and examples include nonlinear modulation and time-of-flight diffraction methods, which are both used to detect very small cracks that might otherwise go undetected even with conventional high frequency ultrasound. Because of the obvious need to test trunnion anchor rods in-situ, rod accessibility becomes limited to only the exposed free end, and remote detection of very small defects becomes significantly more challenging. Commercially, no testing methodology exists that is capable of detecting open or closed microcracks in grease- or grout- immersed steel rods at distances up to 60-70 feet. The properties of the grease or grouts surrounding the rod demand further consideration for system specialization and will be described in more detail later. At present a commercial system is offered from Acoustical Control Systems (ACS), called the A1220 Anker, but its capabilities are limited to macroscopic cracks and defects at a range of ten feet or less. Passive acoustical monitoring technologies, such as acoustic emissions (AE), which listen for crack propagation noise within the material, are not seen as viable for several key reasons. They require expensive hardware that must run continuously and must be immune to background structural and electrical noise. There is no guarantee that the AE frequencies from propagation will not couple out of the rod and be below the threshold detection level. These systems seem better suited to high count post-tensioned cables, such as the ones used on cable stay bridges, where there is little attenuation (i.e. the cables are in air) and the system is attempting to detect total failure of a single wire and not propagation of a defect within post-tension elements.

**Research Approach for Microcrack Detection.** The approach is to develop a non-linear guided wave acoustical system and test method to detect the initiation of defects and characterize their extent before failure. Due to the inherent geometry constraints, the traditional scattering of short wavelength by defects will, in general, not be successful in detection of a closed microcrack. Nonlinear methods have repeatedly demonstrated their success for characterizing low levels of damage, such as progressive fatigue deterioration and intrinsic material weaknesses. Theoretical and experimental research efforts have also addressed key design approaches and explored various embodiments. These include nonlinear impact modulation using different propagation modes and wave types (Eskimov et al. 1999).

**Test Bed.** The post-tension trunnion-anchor-rod test bed was designed to allow for controlled laboratory testing under full-scale field representative conditions (see Figure 2). The test bed allows for the tensioning of four rods along a length of 56 feet. Sleeve material consists of 2-inch schedule-40 pipe, as commonly used in the field, or an oversized pvc, to avoid contact and allow larger immersion layers. Features include injection and access ports and internal embedded acoustical sensors.



Figure 2. Full scale 4-rod test bed during construction and concrete placement.

Data shown in Figure 3 represent echoes from various greased rod assemblies using narrow-band low-loss higher order longitudinal guided wave modes for the 1.25 inch diameter trunnion anchor rod. The top graph in Figure 3 shows the first and second backwall reflections from a tensioned 60 foot rod. The total propagation distance shown here is 240 feet (60 ft, four times). Returns over 500-feet of propagation down a grease-immersed rod have been detected using a heterodyne based phase detector. The bottom graph of Figure 3 shows a reflected signal from a 28 foot rod where the last 3 feet of rod is threaded and fully encased in grout. The smaller first echo shown is from a 0.2 inch deep cut which was first detectable when the cut was approximately 0.1 inch deep. Also captured in test bed experiments were clear echoes from BB gun and hammer impacts. Obvious torsional wave echoes were also received from magnetostrictive and piezoceramic transducers on the greased trunnion rod. These echoes present a beginning point for signal optimization, which can involve specification of frequency, propagation mode, transmitter, receiver, and post processing. More detail is presented below regarding propagation in acoustical waveguides.

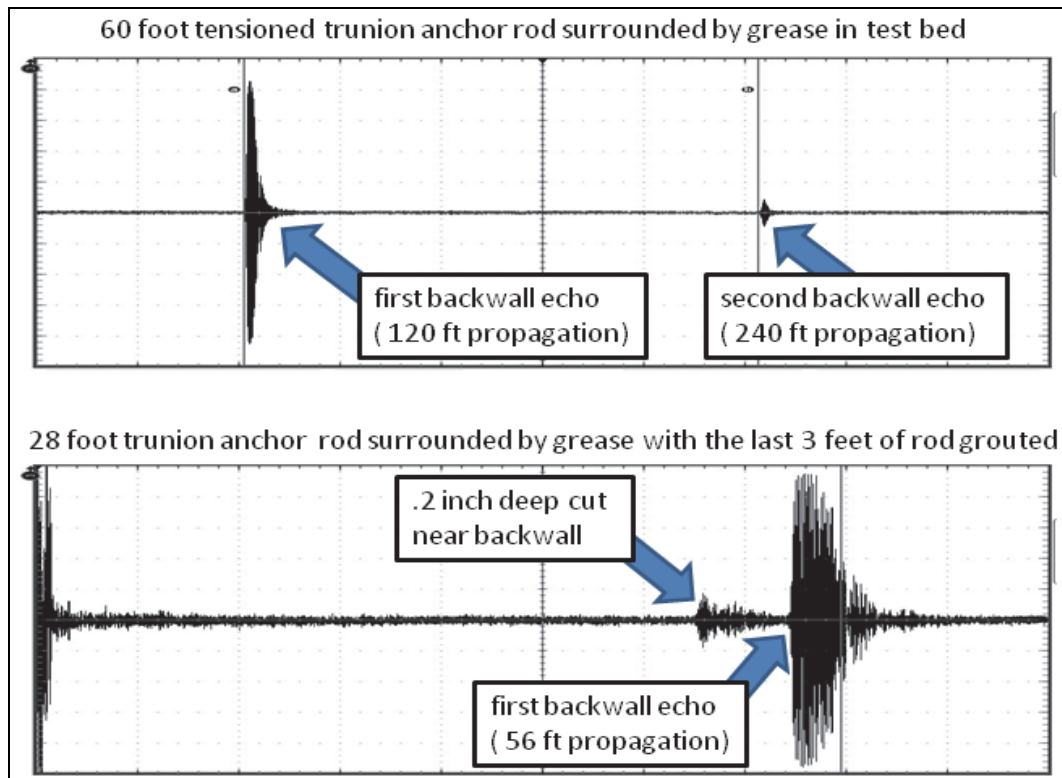


Figure 3. Guided wave echoes from various rod conditions.

**Engineered Defects and Nonlinear Measurement.** For nonlinear experimentation, controlled and simulated defects have been pursued. These have included driven-in shims, polished rods in threaded sleeves, and fatigue of aluminum bars from bending. Future efforts will implement exposure to a localized hydrogen embrittlement solution followed by flexural bending to create orthogonal closed micro-cracking. Loading will, of course, be conservative after quantifying severity. Figure 4 shows some of the simulated crack methods that were used for nonlinear evaluation on rods. These experiments proved successful, with issues regarding transducer coupling nonlinearities coming forward as an important system design consideration.

An example nonlinear measurement recently performed at ERDC is shown in Figure 5. This is an impact modulated torsional wave to detect a crack-simulating defect from hammered-in shims. The modulated sideband frequency is due to nonlinear modulation coming from the shims 'chattering'. Ekimov et al. (1999) discusses a similar setup and also characterized dry and lubricated crack influence on nonlinearity.

**Guided Wave Methods.** Unlike conventional ultrasonic inspection, guided waves allow for high resolution defect detection and characterization at great distances from the applied transducer(s). These methods are well developed for a number of commercial needs including underground and/or coated pipes and rods. When inspection frequencies are high enough, for example when the ultrasonic wavelength is one-tenth the cross-sectional thickness or diameter, the propagation velocities can be treated like an ultrasonic wave propagating in a bulk material with no boundary influence (Rose 1999). At these frequencies, however, ultrasonic propagation characteristics such as attenuation, scatter, and inspection volume, are typically poorly suited to



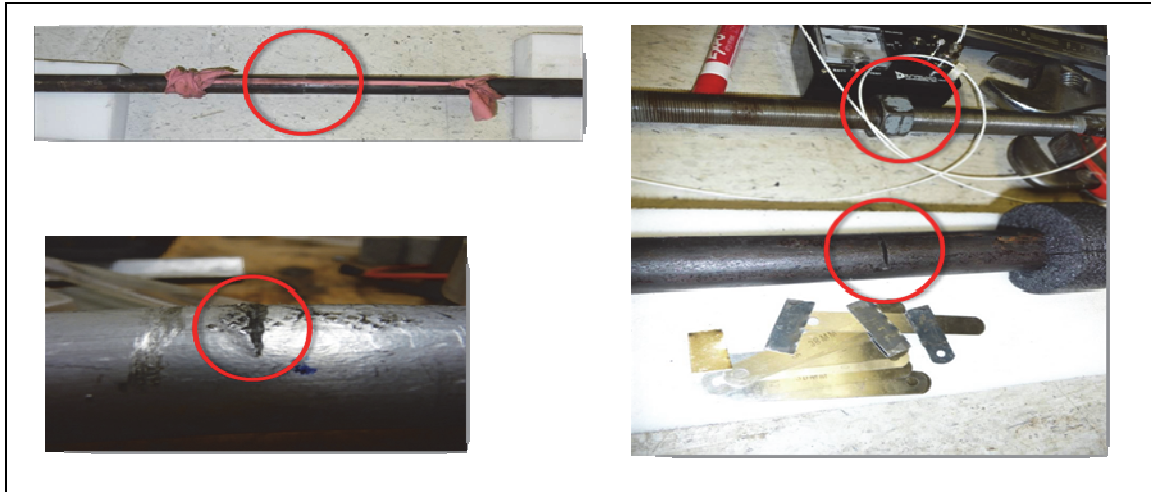


Figure 4. Nonlinear crack simulations: (a) Two polished ends pulled together (b) Fatigued aluminum (c) Nut coupled and shims hammered into a notch.

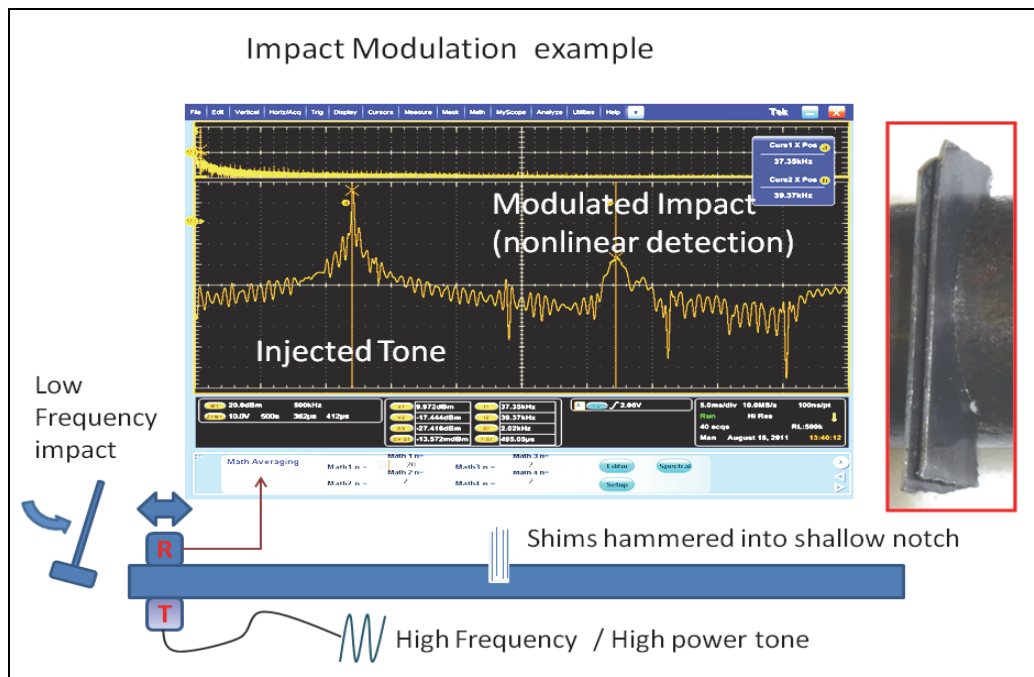


Figure 5. Nonlinear modulation detected using torsional wave and impact modulation.

detection of flaws at long distances. In general, waveguide structures such as plates, rods, pipes and even more arbitrary shaped extrusions like railroad tracks, greatly affect the propagation characteristics of practical or usable ultrasonic frequencies. The cross-sections, material properties, and surrounding materials, together affect how the various propagation modes will perform at different frequencies. The cause of this frequency-based variation in behavior is due to the reflection, refraction, and mode conversion that are perpetually occurring at the material interfaces (Rose 1999). Graphs, called dispersion curves, are used to describe the various phase and group velocity changes that occur with respect to a changing frequency or frequency-diameter product. Note that the dispersion being described here is a waveguide effect and not an intrinsic material

property, as seen in some nonlinear materials. Phase velocity refers to the velocity of a phase point and is used in the development of tuned transducers and in the derivation of the group velocity curves. Group velocity refers to the actual movement speed of a wave packet down the length of the waveguide and is used in determining distances to downrange reflectors such as defects or ends. Group velocity is actual reflected pulse velocity for a given frequency and mode of propagation. These modes and frequencies have in-plane and out-of-plane displacement characteristics that affect attenuation and cross-sectional sensitivity and are often exploited to either minimize propagation losses or control sensitivity at various cross-sectional positions. For example, for a pipe structure, a mode may be selected that minimizes the effect of fluid loading from a material that may be present within the pipe. Likewise, for an attenuative surrounding material like grease or concrete, a mode may be selected which minimizes out-of-plane surface displacement and, hence, reduces signal loss. Energy velocity curves are basically group velocity curves where attenuation calculations have been included (Beard et al. 2003). In determining an inspection mode and frequency, it is also beneficial to select a point of maximum energy velocity to limit the effects of dispersion and to reduce the risk of other modes complicating the detection of the received signal. Propagation modes can be either symmetric or antisymmetric in nature for compressional and shear wave propagation. The compressional or longitudinal energy is characterized by particle displacements that are parallel to the direction of propagation. In bulk material inspection, the compressional wave will travel almost twice as fast as the shear wave energy. The shear wave or transverse wave is characterized by particle motion that is perpendicular to the direction of wave propagation. In general, shear waves exist only in solids and are not carried in fluids. Some greases do have limited capacity in carrying shear waves. Because the viscosity of some grease will vary greatly with seasonal temperature changes, this is a parameter space that will be explored under controlled laboratory conditions. In a rod-like structure, the shear wave particle displacements can either be in the radial direction (transverse shear) or parallel to the surface (horizontal shear or torsional). These two shear modes represent two very different guided wave propagation modes. In general, with guided wave inspection the horizontal shear or torsional mode is usually the more desirable. This is due to the fact that it is composed primarily of in-plane displacement, where there is very little mode conversion and, therefore, this propagation mode tends to be non-dispersive and less attenuated by surrounding media. It has been described in the literature as being capable of “slithering” under clamps and other attenuative type bulkheads. The ability to place a torsional wave transducer all the way around the perimeter of the test piece helps minimize the downrange sensitivity variations that can occur in torsional wave inspection. For pipe structures, focusing methods have been described, such as the total focusing method and flexural torsional focusing (Sun et al. 2005), which can help equalize and, therefore, improve downrange flaw detection. Until, or unless, a clear performer is determined, both the torsional and longitudinal wave modes will be considered for inspection. Shown in Figure 6 are torsional and longitudinal reflections from a shallow 9 mm saw cut. This defect was detectable at 50 ft from the transducer applied end. Plates, pipes, and rods are examples of simple guided wave geometries.

**Rod Waves.** Studies by other researchers for defect detection in rod waveguides, such as rock and soil anchors, are well described in a number of papers (Beard et al. 2003; He et al. 2006; and Yang and Yu 2011). Commercial magnetorestrictive equipment is also used by the power industry in corrosional loss detection using guided waves for rods. Rod inspection favors longitudinal and torsional modes of propagation. The fundamental torsional mode for rod propagation does not undergo frequency based waveguide dispersion, which makes it a good candidate for rod inspection.



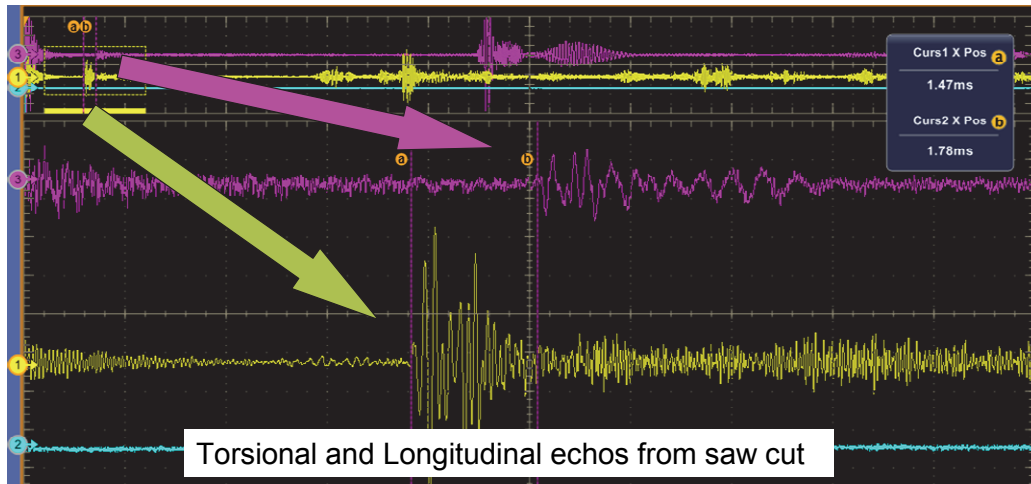


Figure 6. Echoes from reflected longitudinal and shear waves from a saw cut defect.

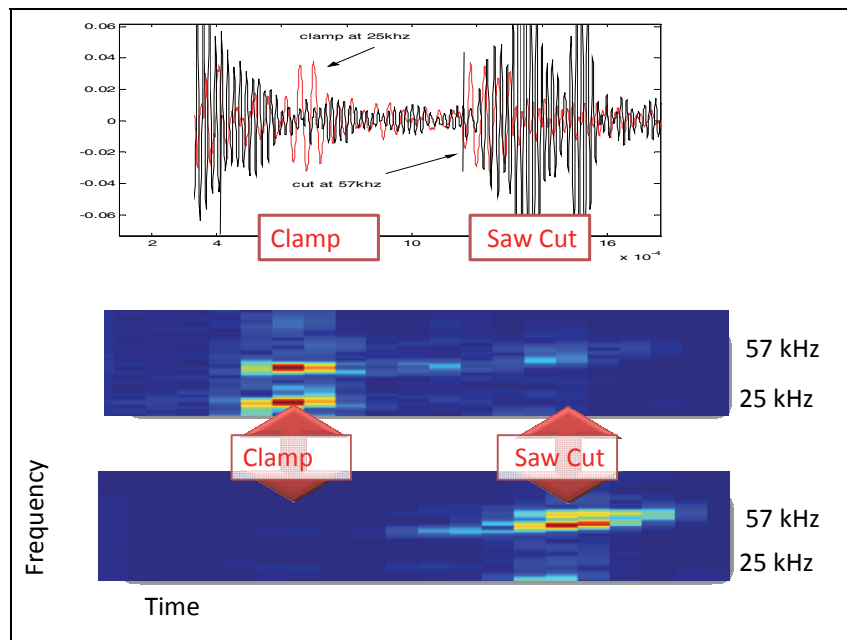


Figure 7. Narrow band tuning remove echoes from clamp which simulates steel on steel contact.

Additionally, the horizontal modes are well suited to ‘slithering’ through bulkheads, sleeve contacts, etc. Generally, modes and frequencies can be determined for the specific inspection purpose desired. This is described for debonding of concrete, cladding, and insulation detection in papers whereby the more attenuated surface-sensing frequencies have shown success up to tens of feet. The low-loss longitudinal modes, with lower surface activity, can likewise be used for backwall detection and nonlinear measurements. The grease or grout is effective at coupling ultrasonic energy out of the trunnion rod and possibly into and back out of the 2-inch schedule-40 sleeve. Tools such as the disperse guided wave simulation software might prove valuable to identify rod echo frequencies that are not dominant in the 2-inch schedule-40 pipe sleeve. Examples of frequency sensitivity can be seen in Figure 7, where a large clamp was placed just

before a saw cut in a trunnion anchor rod. Analysis shows that the clamp reflected more energy near 25 kHz and the crack near 57 kHz. By tuning the system to 57 kHz, the crack could be detected without a false alarm from the clamp.

**Nonlinear Guided Waves.** Guided wave physics applied to the trunnion rod determines how and if certain frequencies and modes will propagate. Nonlinear methods are then designed to operate within these constraints. Electromagnetic Acoustic Transducer (EMATs) and magnetoresistive transducers are additionally useful to remove nonlinearity due to the transducer and test specimen interface. The guided wave based system designs also have to address nonlinear acoustical constraints so the two technologies operate harmoniously. This means selection of not only frequencies which propagate with minimal dispersion, but also which have complementary cross-sectional displacements and adequate sustainment. Examples of modifying these methods to be complementary and/or compromising are described by (Eskimov et al. 1999) and (Pruell et al. 2009).

**ADDITIONAL INFORMATION:** This CHETN is a product of the Condition Assessment of Post-Tensioned Trunnion Anchor Rods Using Non-Linear Acoustics based NDT and other Novel Sensor Techniques Work Unit of the Navigation Systems Research Program being conducted at the US Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory under the management of Eddie Wiggins. Questions about this technical note can be addressed to James Evans (601-634-2535; email: [James.A.Evans@usace.army.mil](mailto:James.A.Evans@usace.army.mil)). This technical note should be cited as follows:

Evans, J. A., Haskins, R. W., Padula, J. A., and Hite, J. E. 2013. *Corps spillway gate trunnion anchor rods: current R&D activities for microcrack detection*. ERDC/CHL CHETN-IX-32. Vicksburg, MS: US Army Engineer Research and Development Center, Vicksburg, MS. <http://chl.erd.c.usace.army.mil/chetn>

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## ACRONYMS AND ABBREVIATIONS

| Term  | Definition   |
|-------|--|
| CHL   | Coastal and Hydraulics Laboratory                  |
| CHETN | Coastal and Hydraulics Engineering Technical Notes |
| Deg   | Degree(s)  |
| DSI   | DWIDAG Systems International                       |
| EM    | Engineering Manual                                 |
| EMAT  | Electromagnetic Acoustic Transducers               |
| ERDC  | Engineer Research and Development Center           |
| F     | Fahrenheit   |
| Ft    | Feet/Foot  |
| In.   | Inch   |
| kHz   | kilo-Hertz   |
| mm    | Millimeter   |
| mHz   | mega-Hertz   |
| NDE   | Non-Destructive Evaluation                         |
| NDT   | Non-Destructive Testing                            |
| PVC   | Polyvinyl-Chloride                                 |
| RARG  | Research Area Review Group                         |
| R&D   | Research and Development                           |
| SON   | Statements of Need                                 |
| WU    | work Unit  |
| USACE | US Army Corps of Engineers                         |

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